# Baryon Elastic and Transition Form Factors

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## Mass in the Standard Model and Consequences of its Emergence

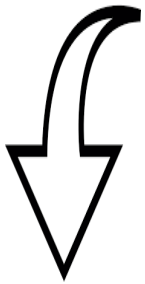
ECT* Workshop April 19-23, 2021

**Emergence**

**Low-level rules producing high-level phenomena with enormous apparent complexity**

Start from the QCD Lagrangian:

$$\mathcal{L}_{\rm QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} + \frac{1}{2\xi}(\partial^\mu A^a_\mu)^2 + \partial^\mu \bar{c}^a \partial_\mu c^a + g\, f^{abc}(\partial^\mu \bar{c}^a) A^b_\mu c^c \,.$$



Lattice-regularized QCD, Continuum Schwinger-function methods, ...

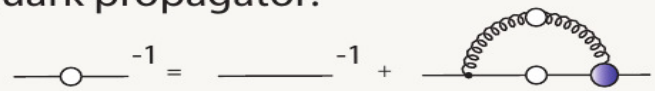
And obtain:

- Dynamical generation of fundamental mass scale in pure Yang-Mills (gluon mass).
- Quark constituent masses and dynamical chiral symmetry breaking.
- Bound state formation: mesons, baryons, glueballs, hybrids, multiquark systems...
- Signals of confinement.

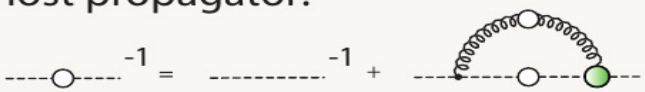
*These (emergent) phenomena is not apparent in the QCD Lagrangian; however, they characterized the nonperturbative regime of QCD where hadrons live*

**Emergent phenomena** *could be associated with dramatic, dynamically driven changes in the analytic structure of QCD's Schwinger functions, which are solutions of the DSEs*

Quark propagator:

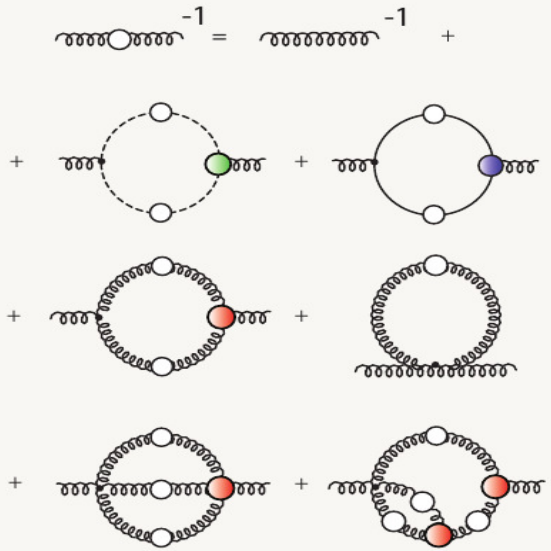



Ghost propagator:

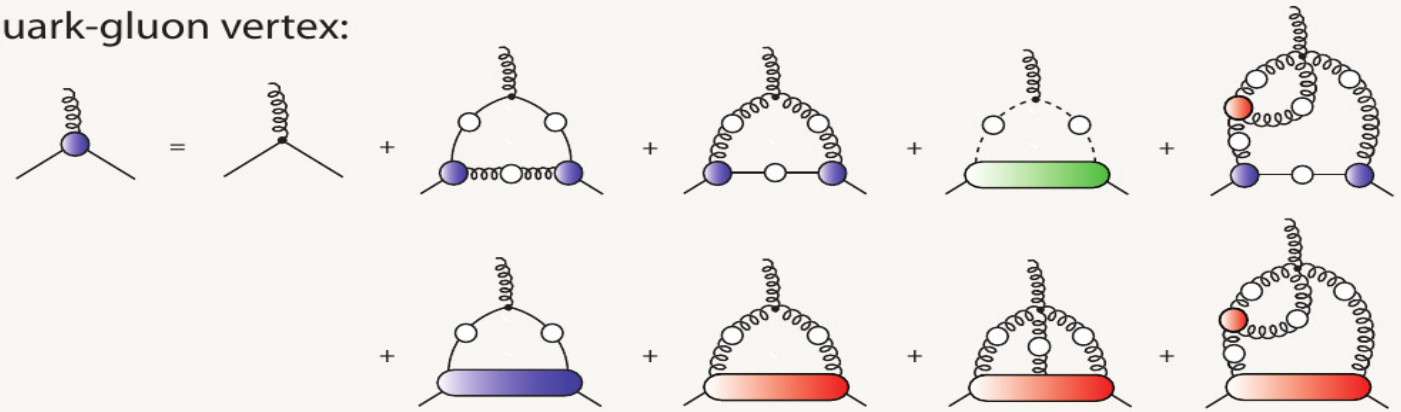



Ghost-gluon vertex:


Gluon propagator:




Quark-gluon vertex:



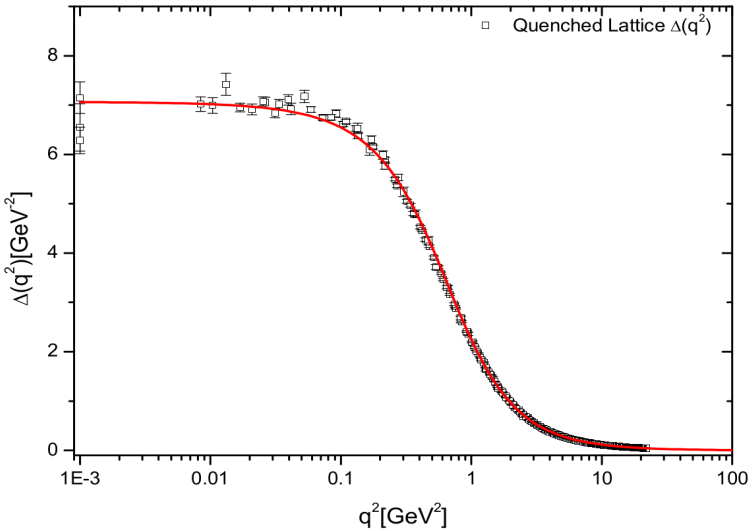
# Non-perturbative QCD: Dynamical generation of gluon mass

☞ Dressed-gluon propagator in Landau gauge:

$$i\Delta_{\mu\nu} = -iP_{\mu\nu}\Delta(q^2), \quad P_{\mu\nu} = g_{\mu\nu} - q_\mu q_\nu / q^2$$

- An inflexion point at $q^2 > 0$.
- Breaks the axiom of reflexion positivity.
- Gluon mass generation $\leftrightarrow$ Schwinger mechanism.

A.C. Aguilar *et al.*, Phys. Rev. D78 (2008) 025010;
I.L. Bogolubsky *et al.*, Phys. Lett. B676 (2009) 69.

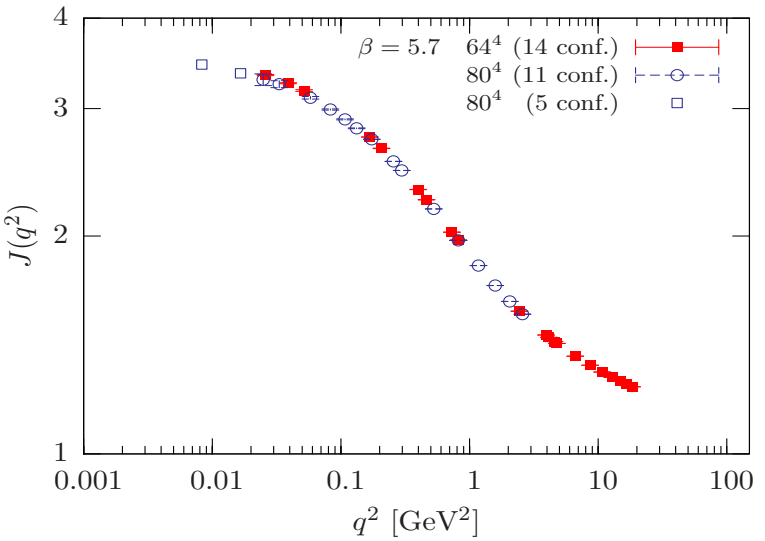



☞ Dressed-ghost propagator in Landau gauge:

$$G^{ab}(q^2) = \delta^{ab}\,\frac{J(q^2)}{q^2}$$

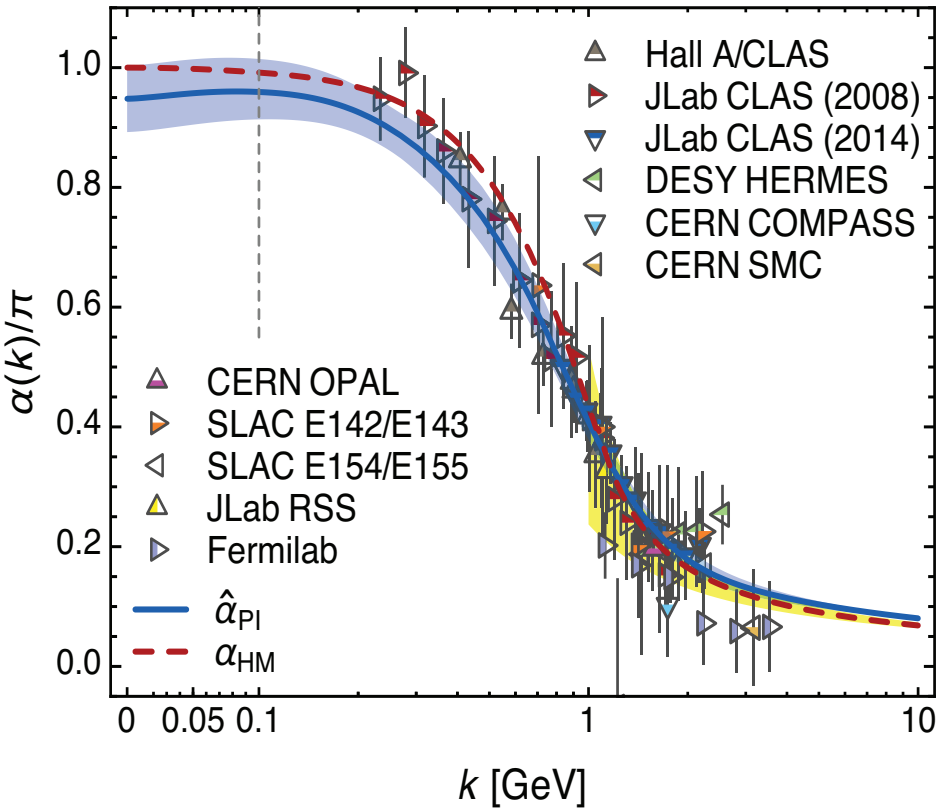
- No power-like singular behavior at $q^2 \to 0$.
- Good indication that $J(q^2)$ reaches a plateau.
- Saturation of ghost's dressing function.

Ph. Boucaud *et al.*, JHEP 0806 (2008) 099;
C. Fischer *et al.*, Annals Phys. 324 (2009) 2408.



# Non-perturbative QCD: Saturation at IR of process-independent effective-charge

D. Binosi *et al.*, Phys. Rev. D96 (2017) 054026;
A. Deur *et al.*, Prog. Part. Nucl. Phys. 90 (2016) 1-74.




- Data = running coupling defined from the Bjorken sum-rule.

$$\int_0^1 dx \left[ g_1^p(x,k^2) - g_1^n(x,k^2) \right] = \frac{g_A}{6} \left[ 1 - \frac{1}{\pi} \alpha_{g_1}(k^2) \right]$$

- Curve determined from combined continuum and lattice analysis of QCD's gauge sector (massless ghost and massive gluon).
- The curve is a running coupling that does NOT depend on the choice of observable.
  - No parameters.
  - No matching condition.
  - No extrapolation.
- It predicts and unifies an enormous body of empirical data via the matter-sector bound-state equations.

- Perturbative regime:

$$\alpha_{g_1}(k^2) = \alpha_{\overline{\rm MS}}(k^2) \left[ 1 + 1.14 \alpha_{\overline{\rm MS}}(k^2) + \dots \right]$$

$$\hat{\alpha}_{\rm PI}(k^2) = \alpha_{\overline{\rm MS}}(k^2) \left[ 1 + 1.09 \alpha_{\overline{\rm MS}}(k^2) + \dots \right]$$

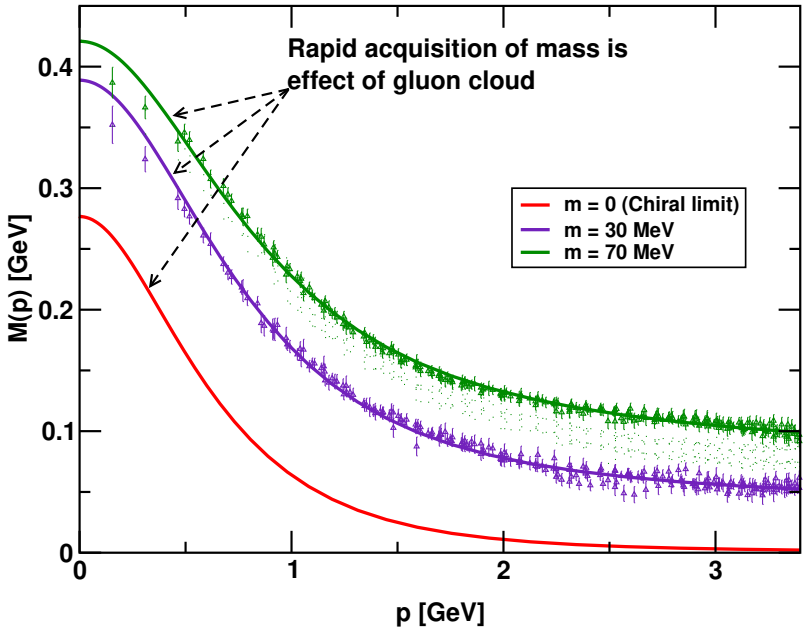
# Non-perturbative QCD: Dynamical generation of quark mass

☞ Dressed-quark propagator in Landau gauge:

$$S^{-1}(p) = Z_2(i\gamma\cdot p + m) + \Sigma(p) = \left(\frac{Z(p^2)}{i\gamma\cdot p + M(p^2)}\right)^{-1}$$

- Mass generated from the interaction of quarks with the gluon-medium.
- Light quarks acquire a HUGE constituent mass.
- Responsible of the 98% of proton's mass, the large splitting between parity partners, ...

M.S. Bhagwat *et al.*, Phys.Rev. C68 (2003) 015203.




☞ Goldberger-Treiman relation at the quark level:

Quark propagator: $S^{-1}(p) = i\gamma\cdot p\, A(p^2) + B(p^2)\,,$

Pion's BS-amplitude: $\Gamma_\pi(p,P) \propto \gamma^5 E_\pi(p;P)\,.$

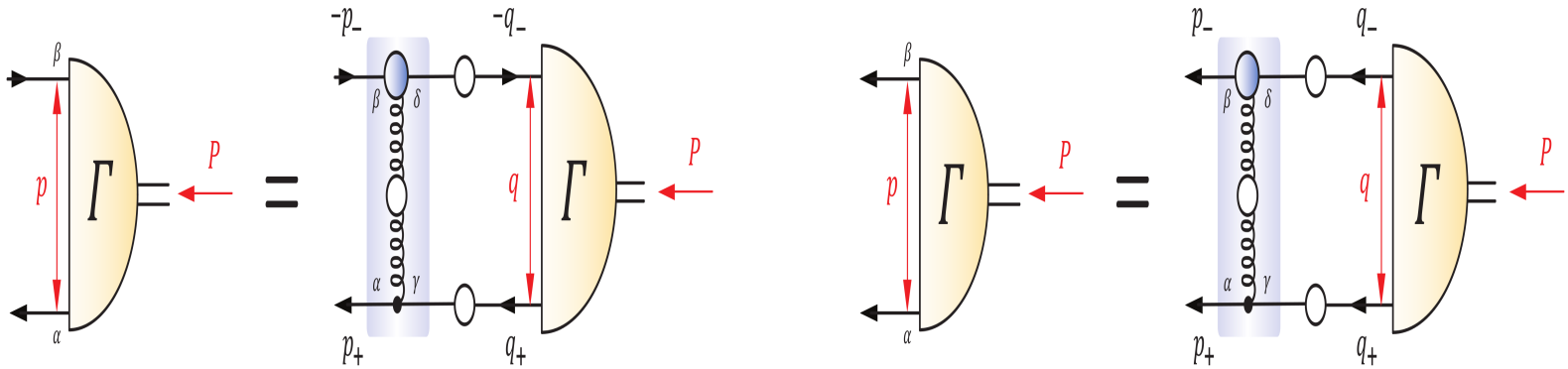
$$f_\pi E_\pi(p;0) = B(p^2)$$

Properties of the massless pion are a direct measure of the dressed-quark mass function

**Cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe**

# Diquark correlations

*Any interaction able to create Goldstone modes as bound-states of light dressed-quark and -antiquark will generate strong $\bar{3}_c$ correlations between any two dressed quarks.*




Meson BSE

Diquark BSE

☞ Owing to properties of charge-conjugation, a diquark with spin-parity $J^P$ may be viewed as a partner to the analogous $J^{-P}$ meson:

$$\Gamma_{q\bar{q}}(p;P) = -\int \frac{d^4q}{(2\pi)^4}\, g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu\, S(q+P)\Gamma_{q\bar{q}}(q;P)S(q)\,\frac{\lambda^a}{2}\,\gamma_\nu$$

$$\Gamma_{qq}(p;P)C^\dagger = -\frac{1}{2}\int \frac{d^4q}{(2\pi)^4}\, g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu\, S(q+P)\Gamma_{qq}(q;P)C^\dagger S(q)\,\frac{\lambda^a}{2}\,\gamma_\nu$$

☞ Whilst no pole-mass exists, the following mass-scales express the strength and range of the correlation:

$$m_{[ud]_{0^+}} = 0.7-0.8\,\text{GeV}, \quad m_{\{uu\}_{1^+}} = 0.9-1.1\,\text{GeV}, \quad m_{\{dd\}_{1^+}} = m_{\{ud\}_{1^+}} = m_{\{uu\}_{1^+}}$$

☞ Diquark correlations are soft, they possess an electromagnetic size:

$$r_{[ud]_{0^+}} \gtrsim r_\pi, \qquad r_{\{uu\}_{1^+}} \gtrsim r_\rho, \qquad r_{\{uu\}_{1^+}} > r_{[ud]_{0^+}}$$

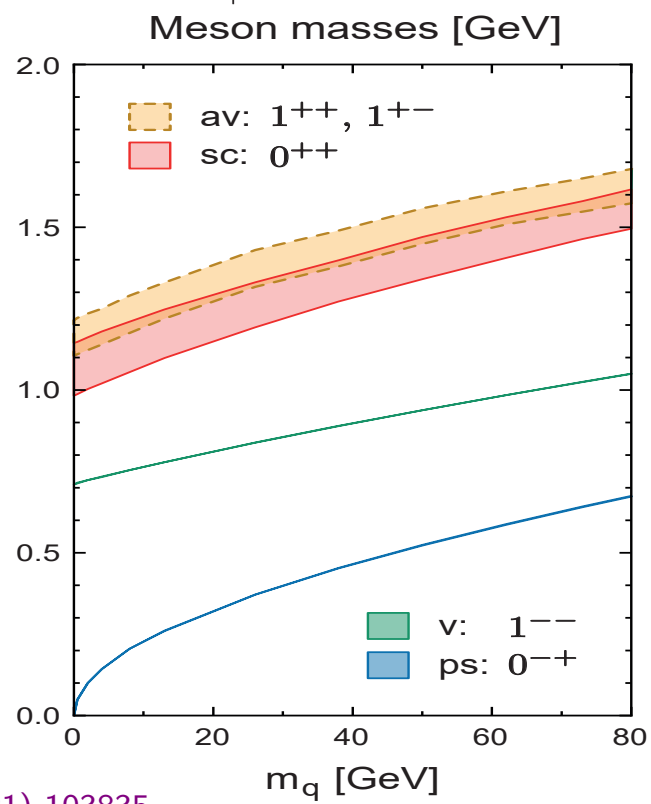
# Diquark species

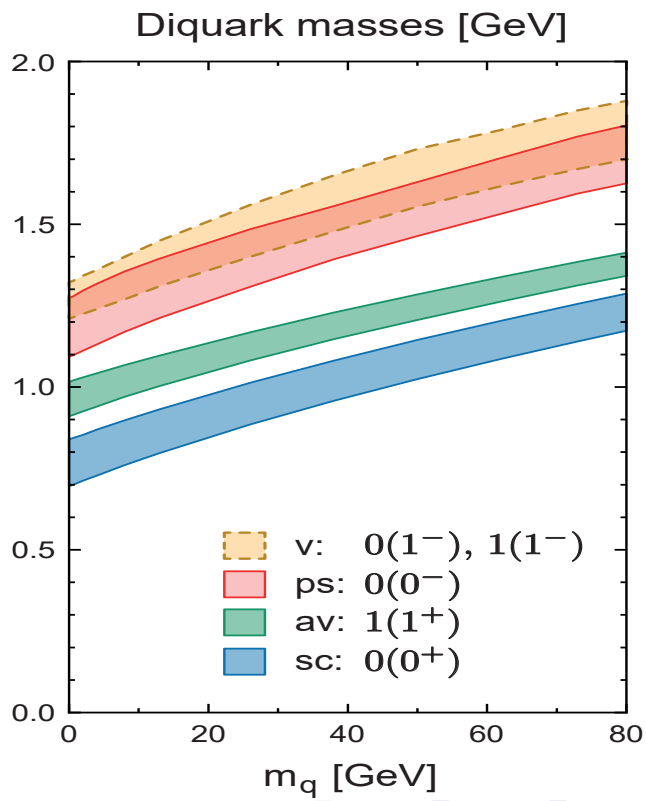
## Octet and decuplet baryons

| | [nn] | {nn} | [ns] | {ns} | {ss} |
|---|---|---|---|---|---|
| $N$ | ● | ● | | | |
| $\Delta$ | | ● | | | |
| $\Lambda$ | ● | | ● | ● | |
| $\Sigma$ | | ● | ● | ● | |
| $\Xi$ | | | ● | ● | ● |
| $\Omega$ | | | | | ● |

## Other baryons as parity partners

- ☞ $[I = 0, J^P = 0^+]$: Isoscalar-scalar.
- ☞ $[I = 1, J^P = 1^+]$: Isovector-pseudovector.
- ☞ $[I = 0, J^P = 0^-]$: Isoscalar-pseudoscalar.
- ☞ $[I = 0, J^P = 1^-]$: Isoscalar-vector.
- ☞ $[I = 1, J^P = 1^-]$: Isovector-vector.



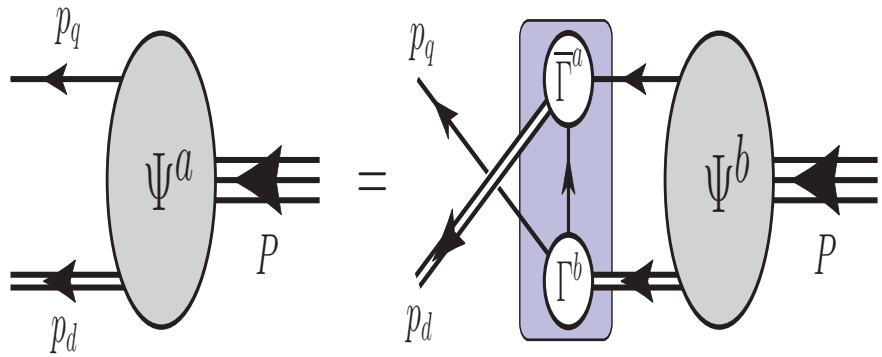




M. Yu. Barabanov *et al.*,
Prog. Part. Nucl. Phys. 116 (2021) 103835

# The quark+diquark structure of a baryon

☞ A baryon can be viewed as a **Borromean bound-state**, the binding within which has two contributions:

- Formation of tight diquark correlations.
- Quark exchange depicted in the shaded area.




☞ The exchange ensures that diquark correlations within the baryon are fully dynamical: no quark holds a special place.

☞ The rearrangement of the quarks guarantees that the baryon's wave function complies with Pauli statistics.

☞ The number of states in the spectrum of baryons obtained is similar to that found in the three-constituent quark model, just as it is in today's LQCD calculations.

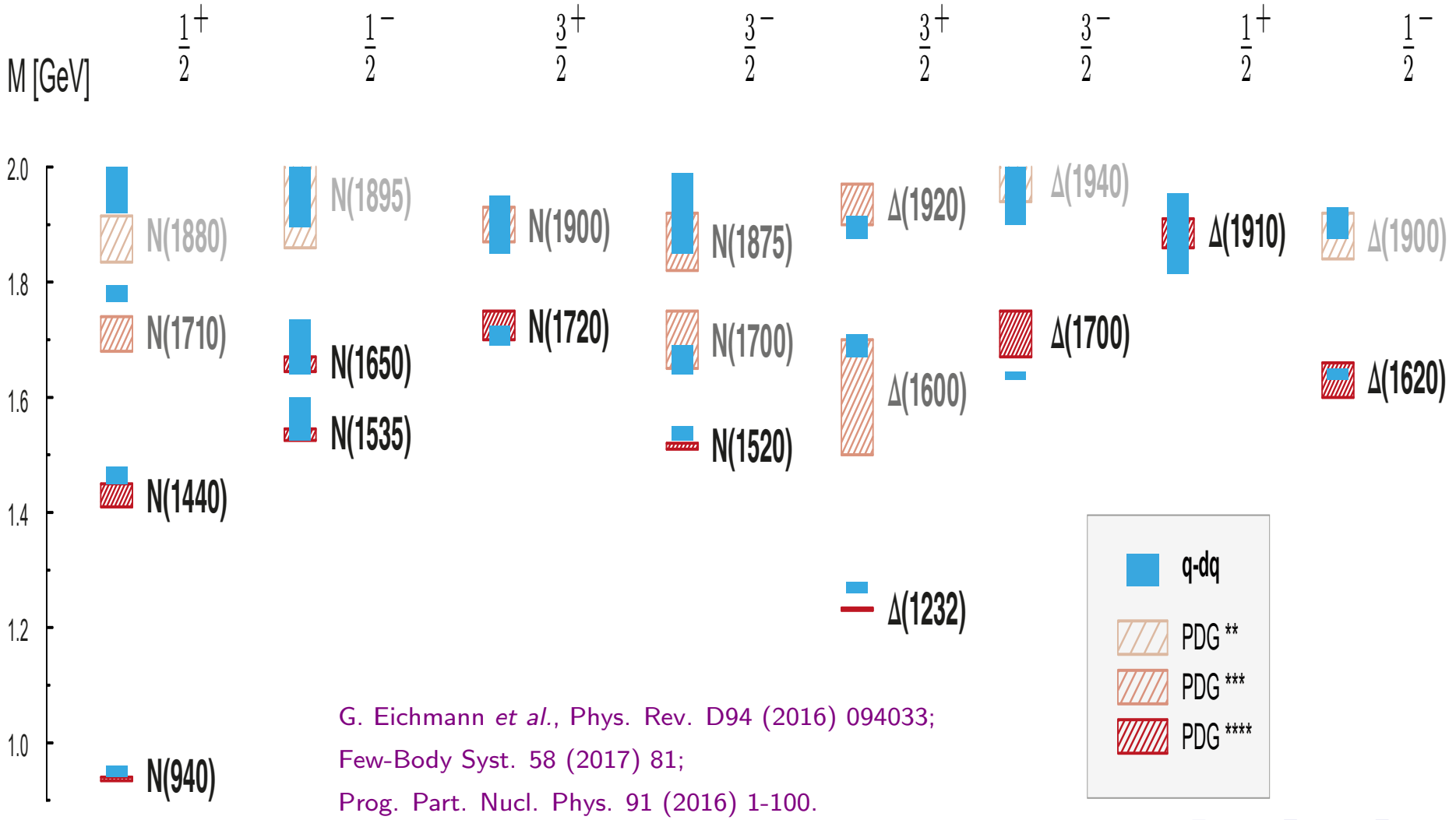
☞ Modern diquarks are different from the old static, point-like diquarks which featured in early attempts to explain the so-called missing resonance problem.

☞ Modern diquarks enforce certain distinct interaction patterns for the singly- and doubly-represented valence-quarks within the baryon.

S.-S. Xu *et al.*, Phys. Rev. D92 (2015) 114034; Y. Lu *et al.*, Phys. Rev. C96 (2017) 015208; C. Chen *et al.*, Phys. Rev. D100 (2019) 054009; P.-L. Yin *et al.*, Phys. Rev. D100 (2019) 034008.

# Baryon spectrum within the quark+diquark picture

- ☞ Spectrum in one to one agreement with experiment.
- ☞ Correct level ordering (without coupled-channels effects).




G. Eichmann *et al.*, Phys. Rev. D94 (2016) 094033;
Few-Body Syst. 58 (2017) 81;
Prog. Part. Nucl. Phys. 91 (2016) 1-100.

**non-relativistic** | **relativistic**

**Mesons:** $P = (-1)^{L+1}$ ~~$P = (-1)^{L+1}$~~

| S | L | $J^{PC}$ |
|---|---|---|
| 0 | 0 | $0^{-+}$ |
| 1 | 0 | $1^{--}$ |
| 0 | 1 | $1^{+-}$ |
| 1 | 1 | $0^{++}$ |

Bethe,Salpeter, Llewelyn-Smith 1950ies

$$\Gamma_\pi(P,p) = \gamma_5 \left[ F_1(P,p) + F_2(P,p) i\not{P} + F_3(P,p) p\!\cdot\!P\, i\not{p} + F_4(P,p) [\not{p}, \not{P}] \right]$$

s-wave

p-wave

**Baryons:** $P = (-1)^{L}$ ~~$P = (-1)^{L}$~~

| S | L | $J^{P}$ |
|---|---|---|
| 1/2 | 0 | $1/2^{+}$ |
| 3/2 | 2 | |

| $J^P$ | total | s-wave | p-wave | d-wave | f-wave |
|---|---|---|---|---|---|
| 1/2+ | 64 | 8 | 36 | 20 | |
| 3/2+ | 128 | 4 | 36 | 60 | 28 |

# Studies of N* photo- and electro-couplings

**Transition form factors of nucleon resonances**

Unique window into their quark and gluon structure → Distinctive information on the roles played by emergent phenomena in QCD

Broad range of photon virtuality → Probe the excited nucleon structures at perturbative and non-perturbative QCD scales

*A vigorous experimental program has been and is still under way worldwide*

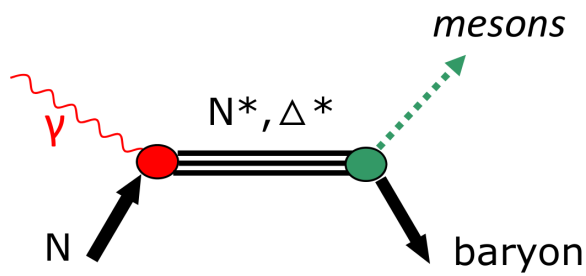
*CLAS, CBELSA, GRAAL, MAMI and LEPS*

☞ Multi-GeV polarized cw beam, large acceptance detectors, polarized proton/neutron targets.

☞ Very precise data for 2-body processes in wide kinematics (angle, energy): $\gamma p \to \pi N$, $\eta N$, $KY$.

☞ More complex reactions needed to access high mass states: $\pi\pi N$, $\pi\eta N$, $\omega N$, $\phi N$, ...

**Extract s-channel resonances**



# Nucleon Resonance Photo-/Electrocouplings Determined from Analyses of Experimental Data on Exclusive Meson Electroproduction off Protons

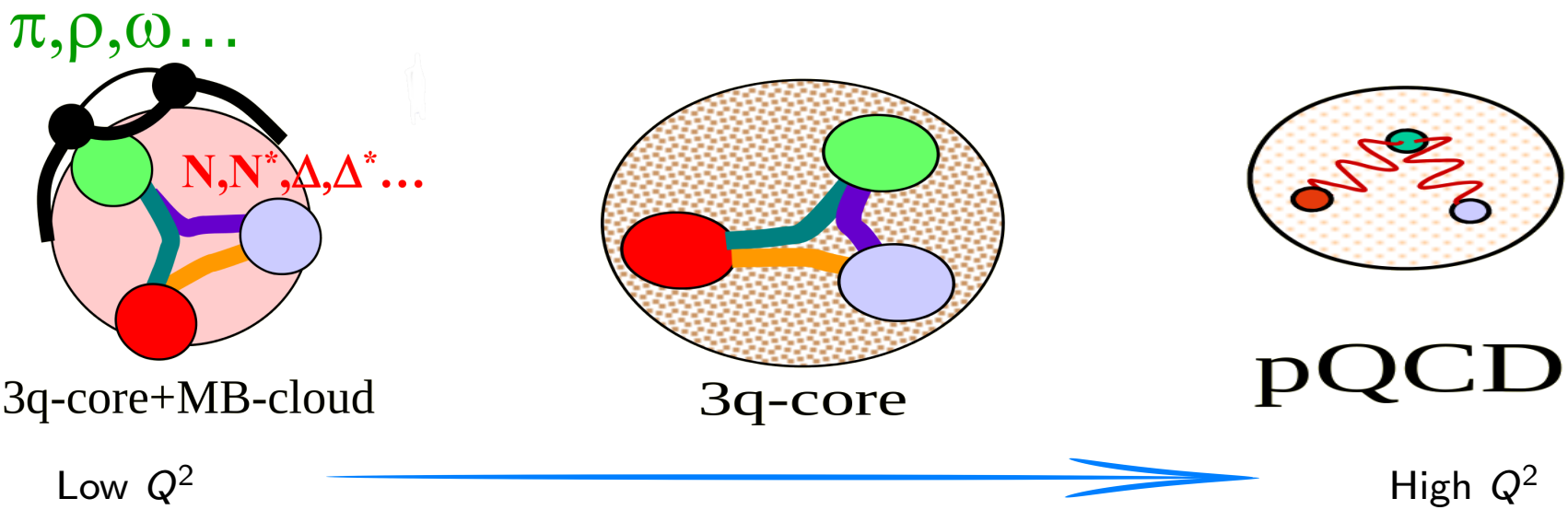
Definition (docx) of $A_{1/2}$, $A_{3/2}$ and $S_{1/2}$ electrocouplings
(in pdf format)

Links to the files with electropcoupling values (docx marked by resonance symbols/unmarked pdf)

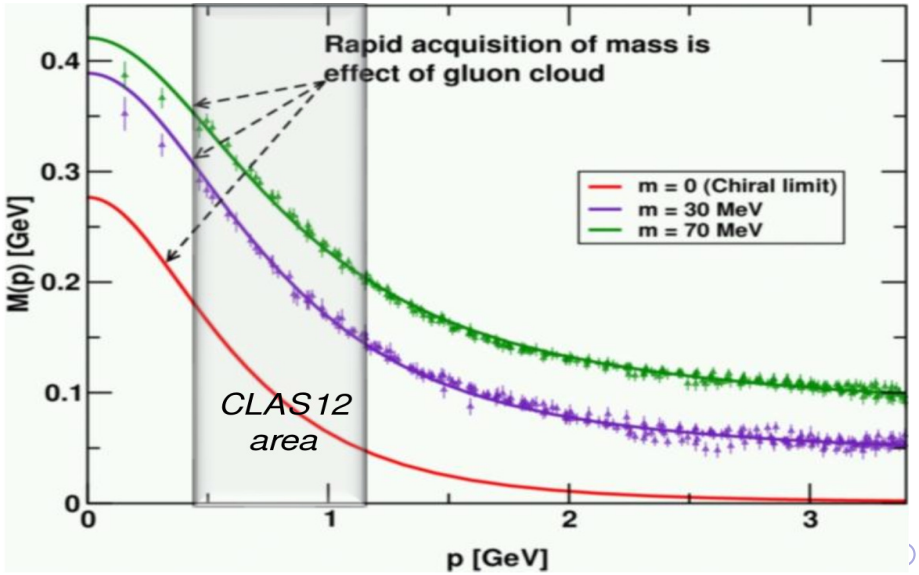
| $\Delta(1232)3/2^+$ | $N(1440)1/2^+$ | $N(1520)3/2^-$ | $N(1535)1/2^-$ | $\Delta(1620)1/2^-$ | $N(1650)1/2^-$ |
|---|---|---|---|---|---|
| pdf | pdf | pdf | pdf | pdf | pdf |
| $N(1675)5/2^-$ | $N(1680)5/2^+$ | $\Delta(1700)3/2^-$ | $N(1710)1/2^+$ | $N(1720)3/2^+$ | |
| pdf | pdf | pdf | pdf | pdf | |

https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

☞ CLAS12 aims to measure the $N^*$ photo- and electro-couplings at $Q^2$ ever achieved so far and thus trying to distinguish between different effective degrees of freedom.




☞ CLAS12 will be able to extract information about fundamental quantities in QCD at an intermediate energy region.



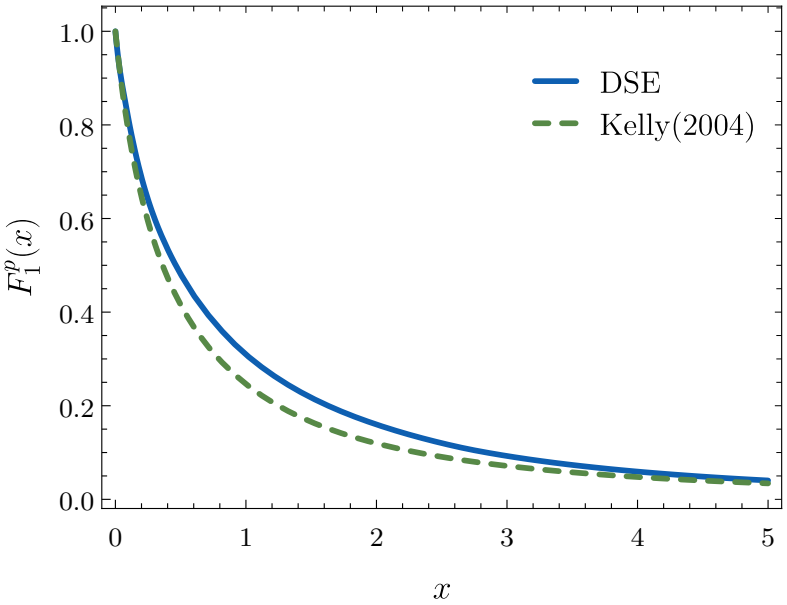
# $\gamma^* N(940)\frac{1}{2}^+ \to N(940)\frac{1}{2}^+$

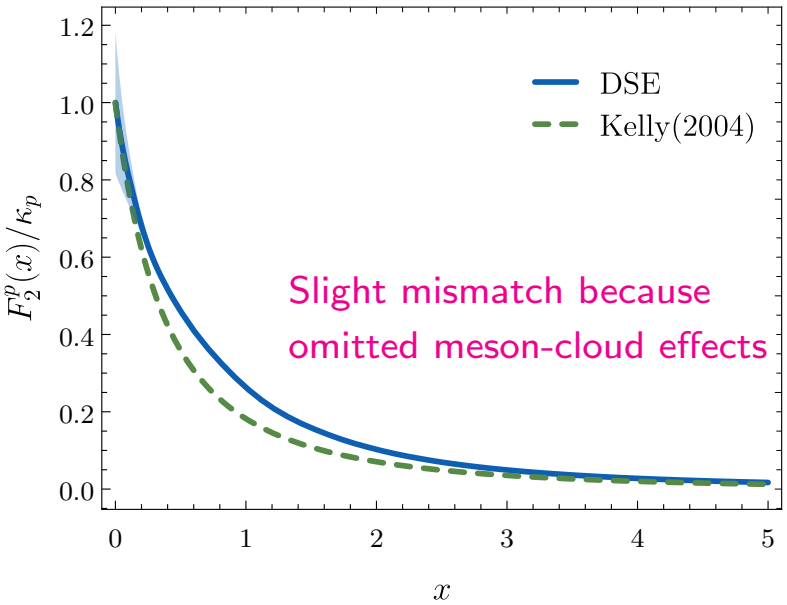
Based on:

- **Nucleon elastic form factors at accessible large spacelike momenta**
  Z.-F. Cui, C. Chen, D. Binosi, F. De Soto, C.D. Roberts, J. Rodríguez-Quintero, S.M. Schmidt and J. Segovia
  Phys. Rev. D102 (2020) 014043, arXiv:hep-ph/2003.11655
- **PDAs: Revealing correlations within the proton and Roper**
  C. Mezrag, J. Segovia, L. Chang and C.D. Roberts
  Phys. Lett. B783 (2018) 263-267, arXiv:nucl-th/1711.09101
- **Understanding the nucleon as a borromean bound-state**
  J. Segovia, C.D. Roberts and S.M. Schmidt
  Phys. Lett. B750 (2015) 100-106, arXiv:nucl-th/1506.05112
- **Nucleon and Delta elastic and transition form factors**
  J. Segovia, I.C. Cloët, C.D. Roberts and S.M. Schmidt
  Few-Body Syst. 55 (2014) 1185-1222, arXiv:nucl-th/1408.2919

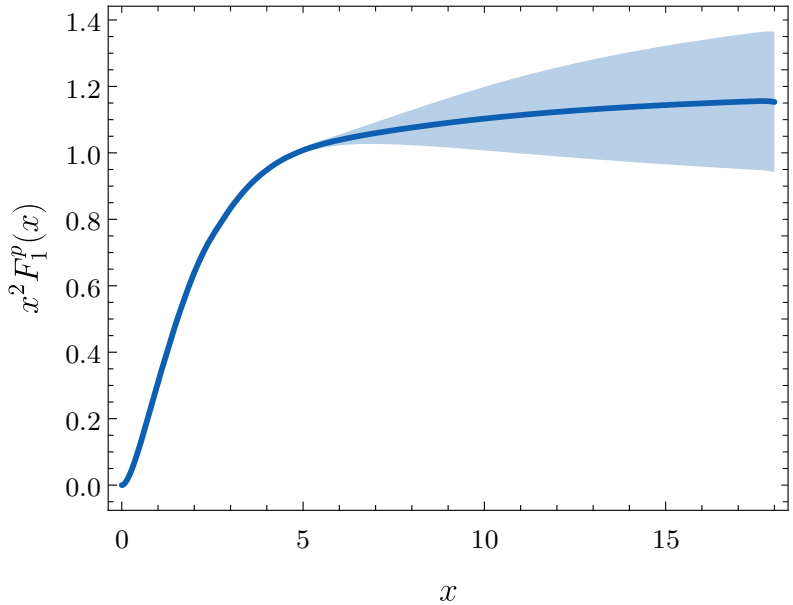
# Proton's Dirac and Pauli form factors

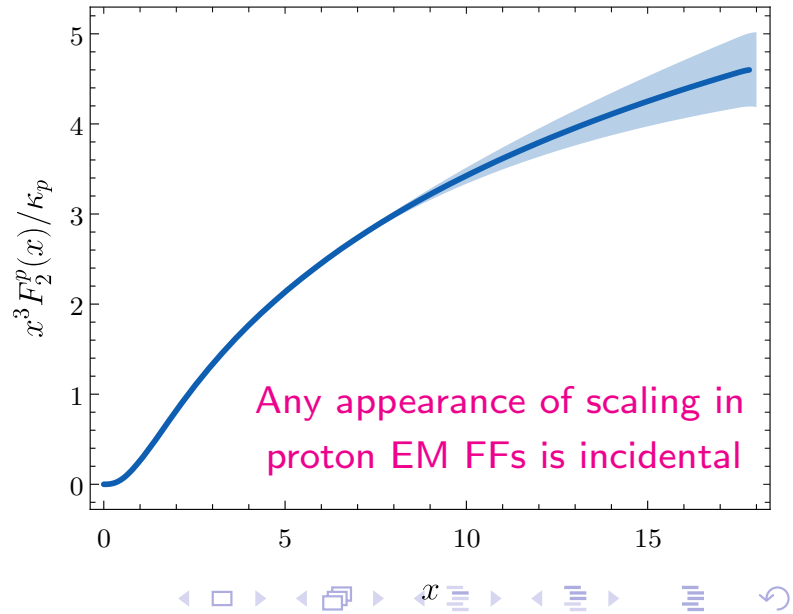
☞ Comparison with experiment:



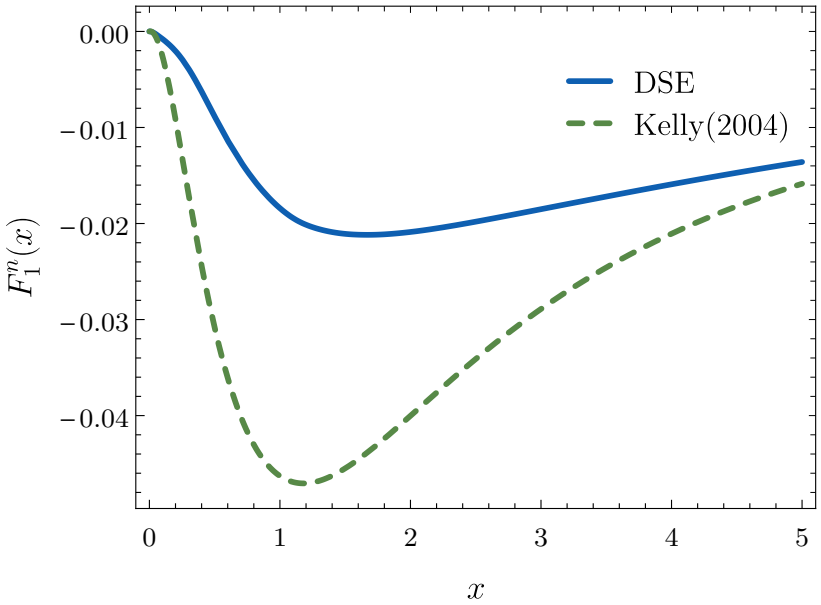

☞ Comparison with perturbative QCD:

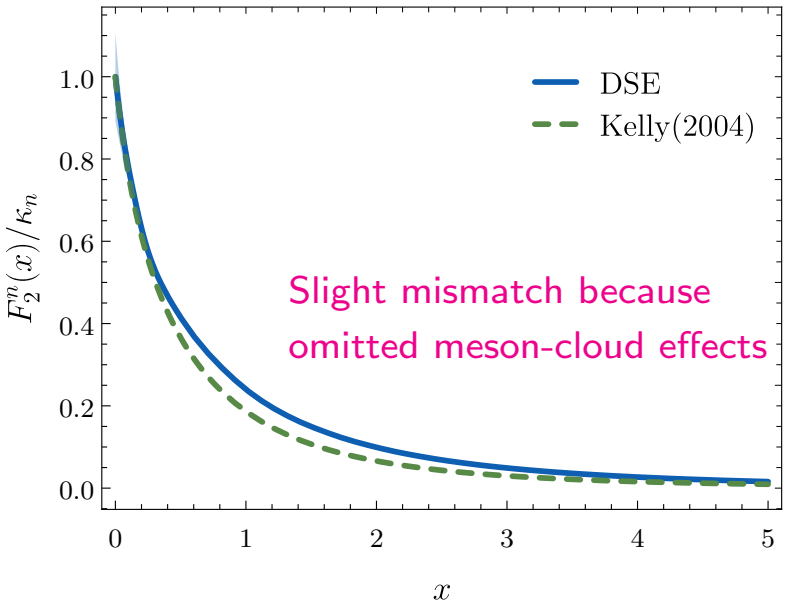


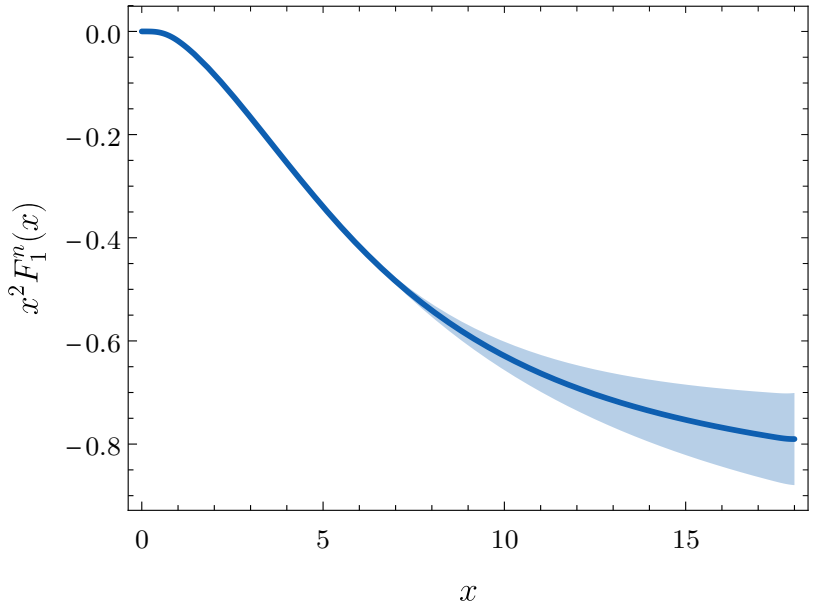
# Neutron's Dirac and Pauli form factors

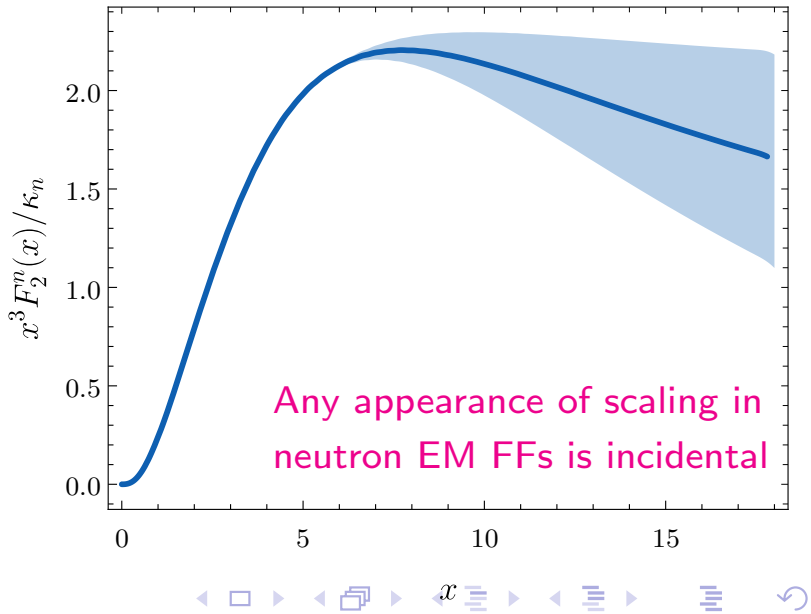
☞ Comparison with experiment:



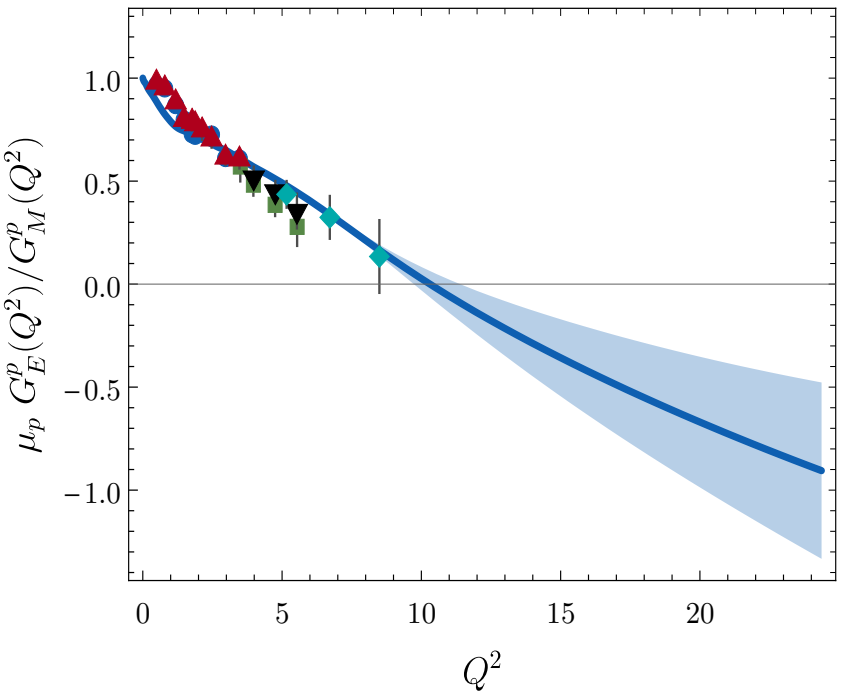



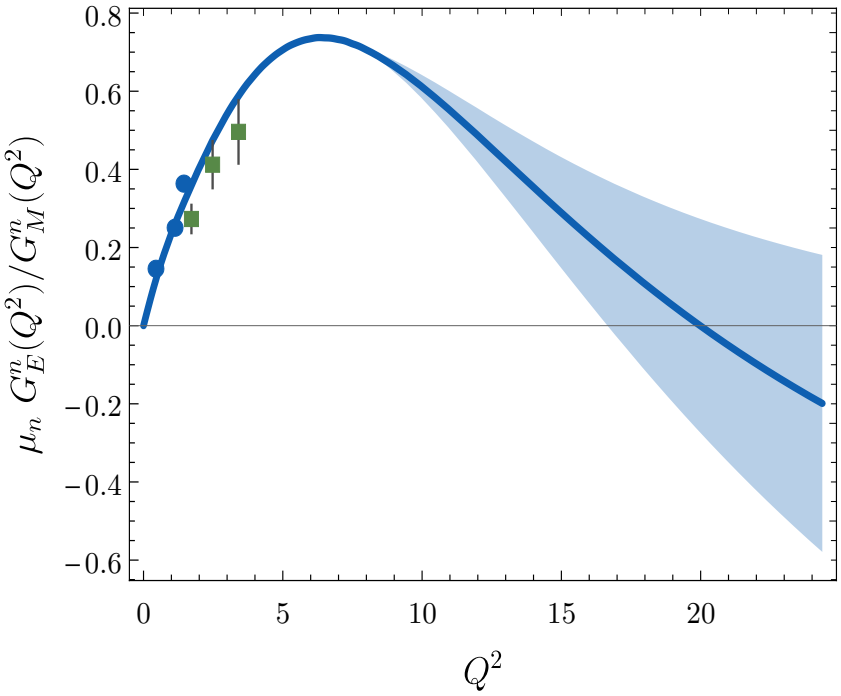

☞ Comparison with perturbative QCD:



# Unit-normalized ratio of Sachs electric and magnetic form factors



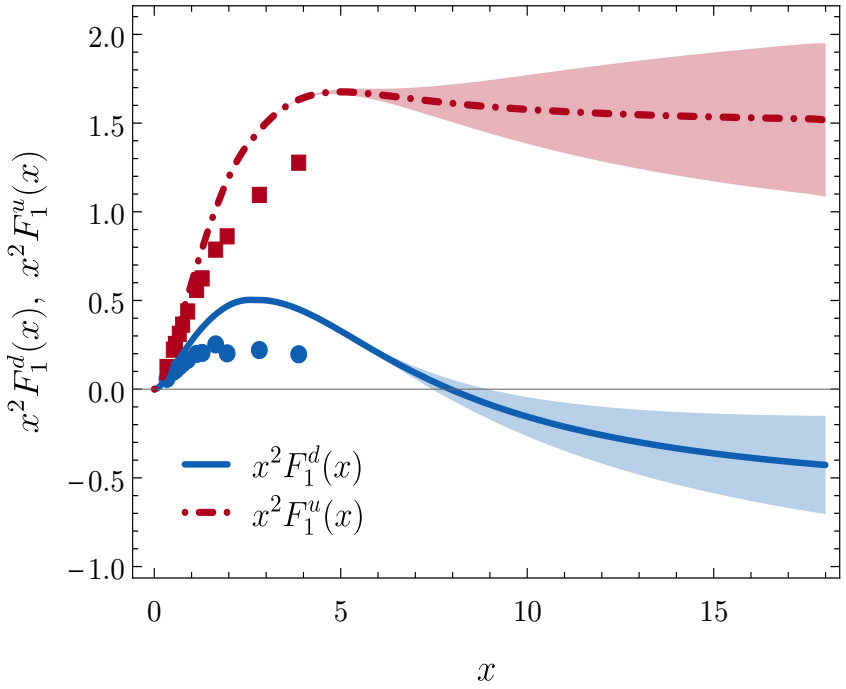



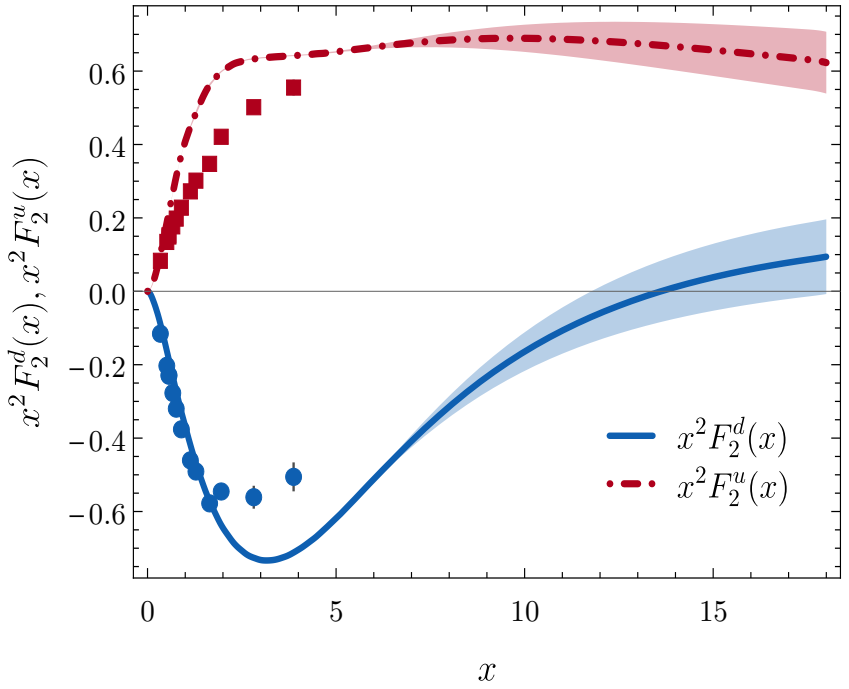

Z.-F. Cui *et al.*, Phys. Rev. D102 (2020) 014043.

☞ Observations:

- There is no evidence for scaling in Dirac and Pauli form factors, and thus in the electromagnetic Sach form factors.
- Our analysis predicts a zero for the proton's electromagnetic ratio at $Q^2 = 10.3^{+1.1}_{-0.7}\,\mathrm{GeV}^2$.
- The neutron's electromagnetic ratio has a peak at $Q^2 \approx 6\,\mathrm{GeV}^2$ and then crossed zero for $Q^2 = 20.1^{+10.6}_{-3.5}\,\mathrm{GeV}^2$.
- All these features can be related with both quark-quark and angular momentum correlations within the nucleon.

# Implications of diquark correlations




☞ Observations:

- $F_1^d$ is smaller than $F_1^u$, even allowing for the difference in normalisation, and decreases more quickly as $x$ increases.
- The location of the zero in $F_1^d$ is a measure of the relative probability of finding pseudovector and scalar diquarks in the proton.
- The $u$- and $d$-quark Pauli form factors are roughly equal in magnitude on $x \lesssim 5$; *i.e.* $F_2^d$ is suppressed with respect $F_2^u$ but only at large momentum transfer.
- There are contributions playing an important role in $F_2$, like the anomalous magnetic moment of dressed-quarks or meson-baryon final-state interactions.

# $\gamma^* N(940)\frac{1}{2}^+ \longrightarrow N(1440)\frac{1}{2}^+$

Based on:

- **Nucleon-to-Roper electromagnetic transition form factors at large $Q^2$**
  C. Chen, Y. Lu, D. Binosi, C.D. Roberts, J. Rodríguez-Quintero, and J. Segovia
  Phys. Rev. D99 (2019) 034013, arXiv:nucl-th/1811.08440
- **Structure of the nucleon's low-lying excitations**
  C. Chen, B. El-Benich, C.D. Roberts, S.M. Schmidt, J. Segovia and S. Wan
  Phys. Rev. D97 (2018) 034016, arXiv:nucl-th/1711.03142
- **Dissecting nucleon transition electromagnetic form factors**
  J. Segovia and C.D. Roberts
  Phys. Rev. C94 (2016) 042201(R), arXiv:nucl-th/1607.04405
- **Completing the picture of the Roper resonance**
  J. Segovia, B. El-Bennich, E. Rojas, I.C. Cloët, C.D. Roberts, S.-S. Xu and H.-S. Zong
  Phys. Rev. Lett. 115 (2015) 171801, arXiv:nucl-th/1504.04386

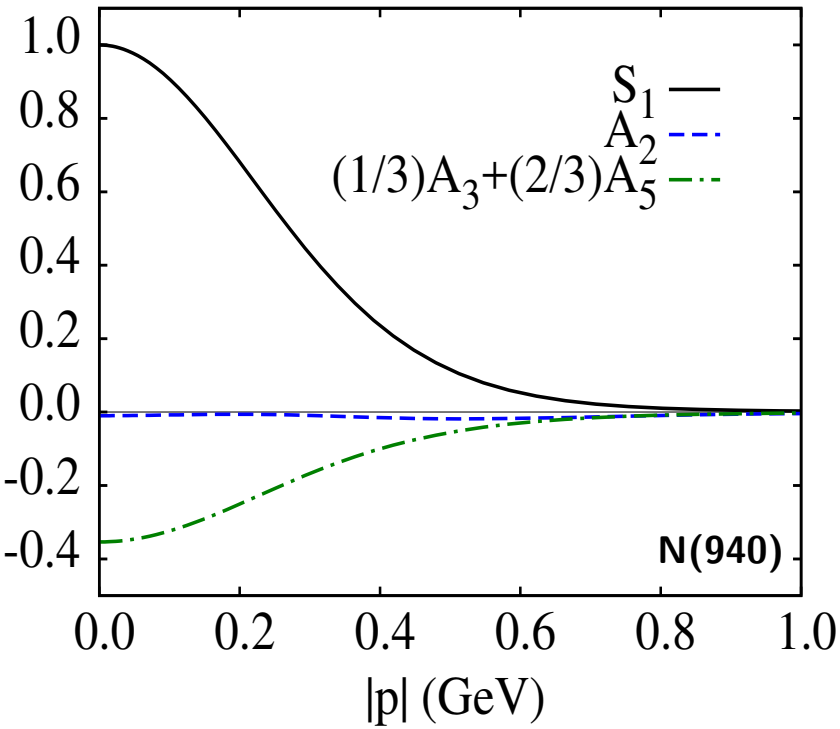
*Bare-states of nucleon resonances correspond to hadron structure calculations which exclude the coupling with the meson-baryon final-state interactions*

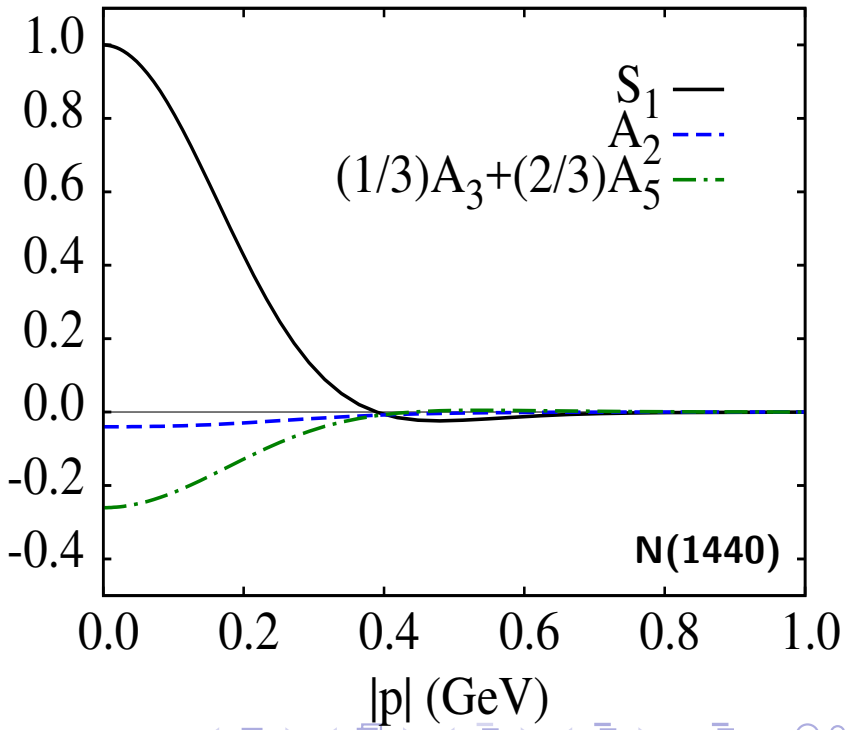
$$M_{Roper}^{DSE} = 1.73\,\mathrm{GeV} \qquad M_{Roper}^{EBAC} = 1.76\,\mathrm{GeV}$$

☞ Observations:

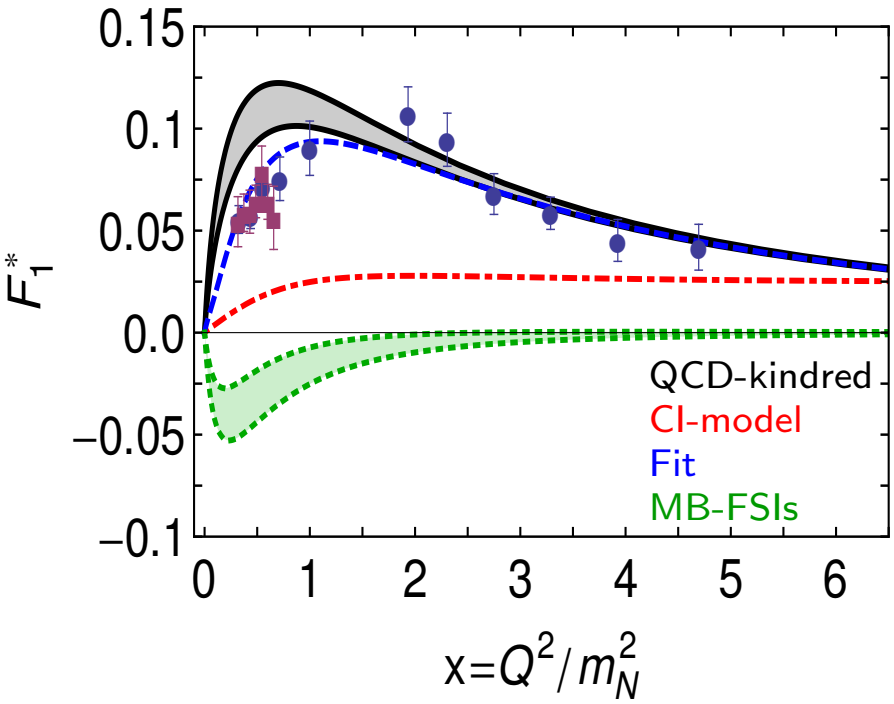
- Meson-Baryon final state interactions reduce dressed-quark core mass by 20%.
- Roper and Nucleon have very similar wave functions and diquark content.
- A single zero in S-wave components of the wave function ⇒ A radial excitation.

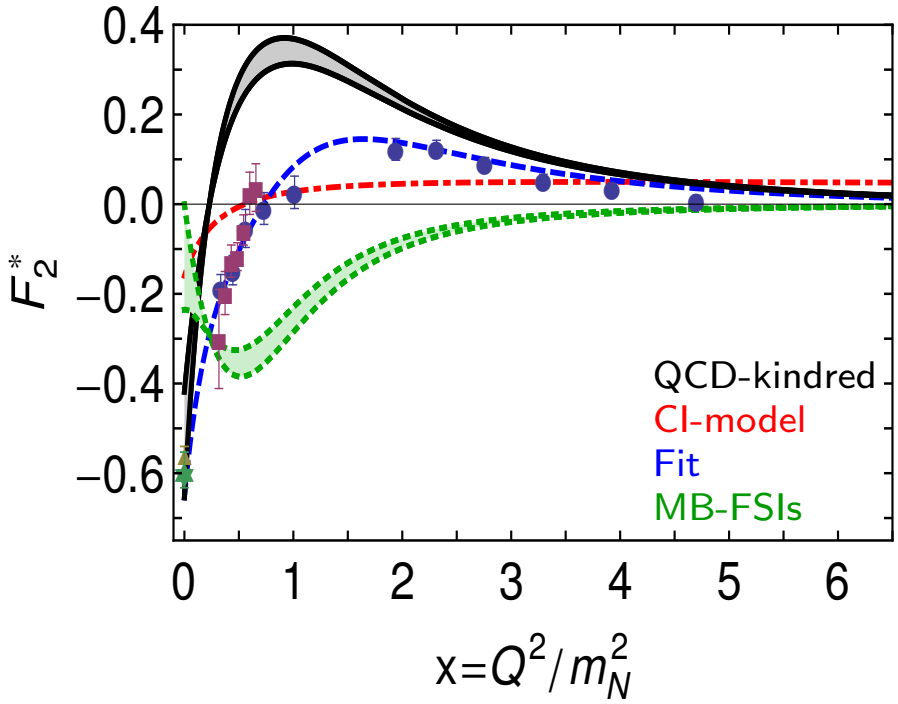
0th Chebyshev moment of the S-wave components



*Nucleon-to-Roper transition form factors at high virtual photon momenta penetrate the meson-cloud and thereby illuminate the dressed-quark core*

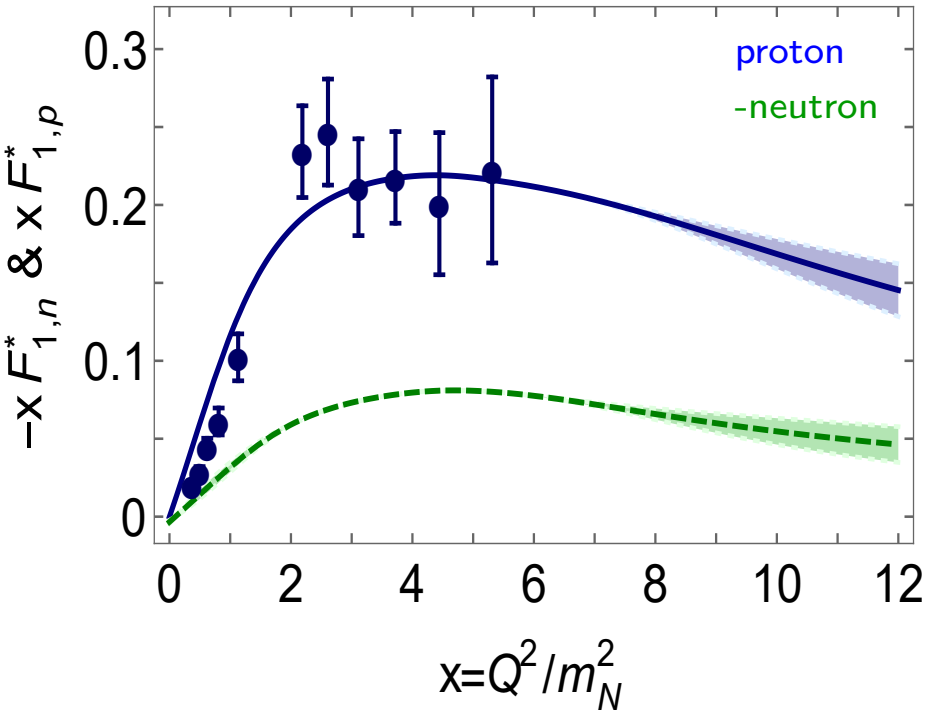


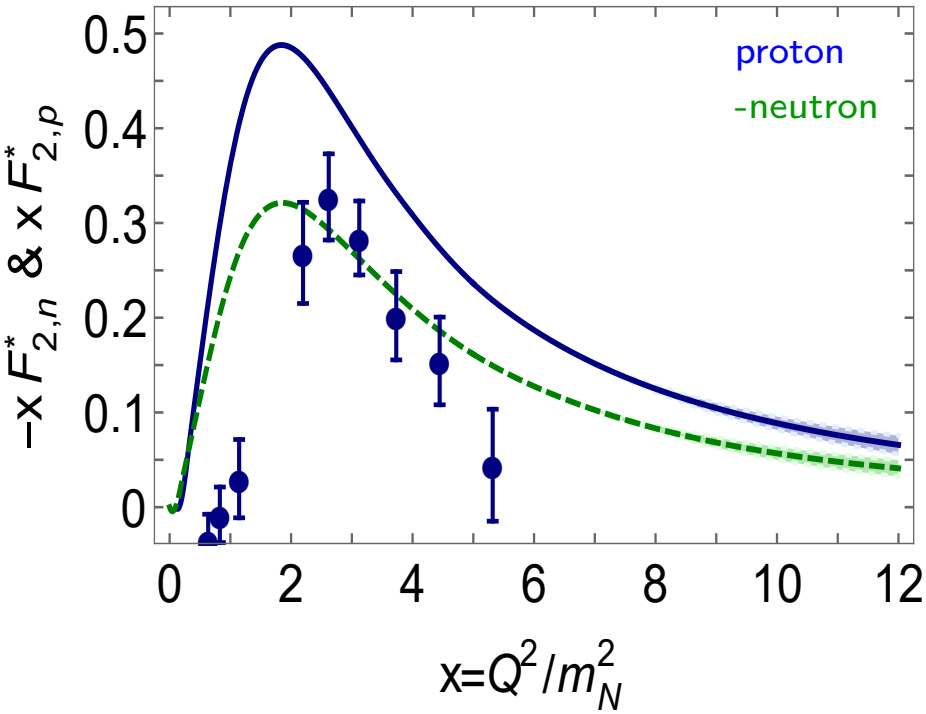




☞ Observations:

- Our calculation agrees quantitatively in magnitude and qualitatively in trend with the data on $x \gtrsim 2$.
- The mismatch between our prediction and the data on $x \lesssim 2$ is due to meson cloud contribution.
- The dotted-green curve is an inferred form of meson cloud contribution from the fit to the data.

*CLAS12 detector at JLab will deliver data on the Roper-resonance electroproduction form factors out to $Q^2 \sim 12 m_N^2$ in both the charged and neutral channels*




☞ Observations:

- On the domain depicted, there is no indication of the scaling behavior expected of the transition form factors: $F_1^* \sim 1/x^2$, $F_2^* \sim 1/x^3$.
- Since each dressed-quark in the baryons must roughly share the momentum, $Q$, we expect that such behaviour will only become evident on $x \gtrsim 20$.

# $\gamma^* N(940)\frac{1}{2}^+ \to \Delta(1232)\frac{3}{2}^+$

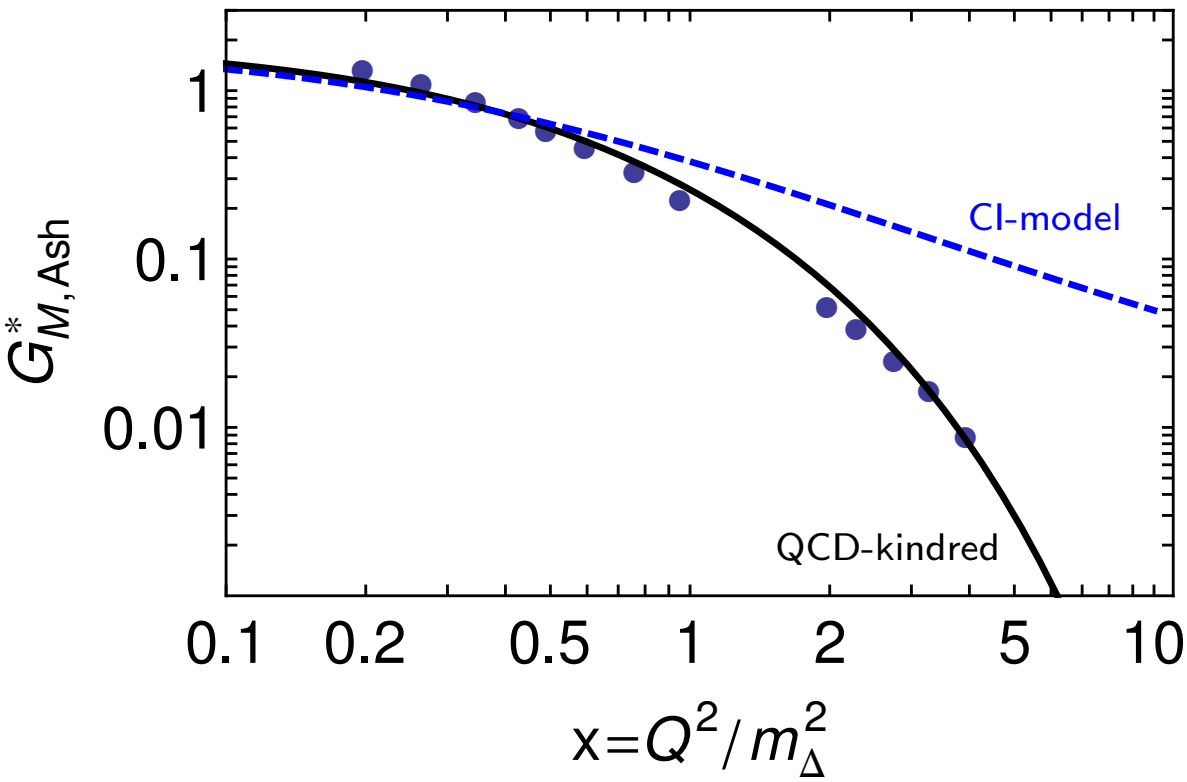
Based on:

- **Dissecting nucleon transition electromagnetic form factors**
  J. Segovia and C.D. Roberts
  Phys. Rev. C94 (2016) 042201(R), arXiv:nucl-th/1607.04405
- **Nucleon and Delta elastic and transition form factors**
  J. Segovia, I.C. Cloët, C.D. Roberts and S.M. Schmidt
  Few-Body Syst. 55 (2014) 1185-1222, arXiv:nucl-th/1408.2919
- **Elastic and transition form factors of the $\Delta(1232)$**
  J. Segovia, C. Chen, I.C. Cloët, C.D. Roberts, S.M. Schmidt and S. Wan
  Few-Body Syst. 55 (2014) 1-33, arXiv:nucl-th/1308.5225
- **Insights into the $\gamma^* N \to \Delta$ transition**
  J. Segovia, C. Chen, C.D. Roberts and S. Wan
  Phys. Rev. C88 (2013) 032201(R), arXiv:nucl-th/1305.0292

# The magnetic dipole form factor in the Ash convention

*Presentations of experimental data typically use the Ash convention*

*– $G^*_{M,Ash}(Q^2)$ falls faster than a dipole –*




- No sound reason to expect:

  $G^*_{M,\mathrm{Ash}}/G_M \sim$ constant

- Jones-Scadron must exhibit:

  $G^*_{M,\mathrm{J\text{-}S}}/G_M \sim$ constant

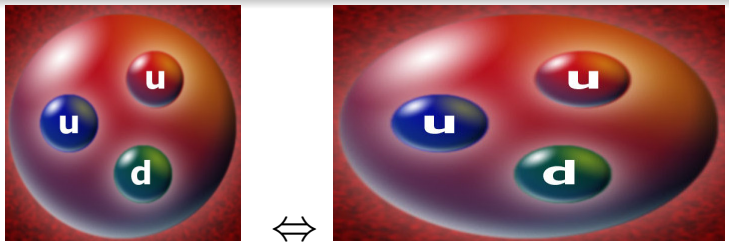
- Meson-cloud effects
  - Up-to 35% for $Q^2 \lesssim 2.0 m_\Delta^2$.
  - Soft $\rightarrow$ disappear rapidly.

- $G^*_{M,\mathrm{Ash}}$ vs $G^*_{M,\mathrm{J\text{-}S}}$
  - A Difference of $1/\sqrt{Q^2}$.

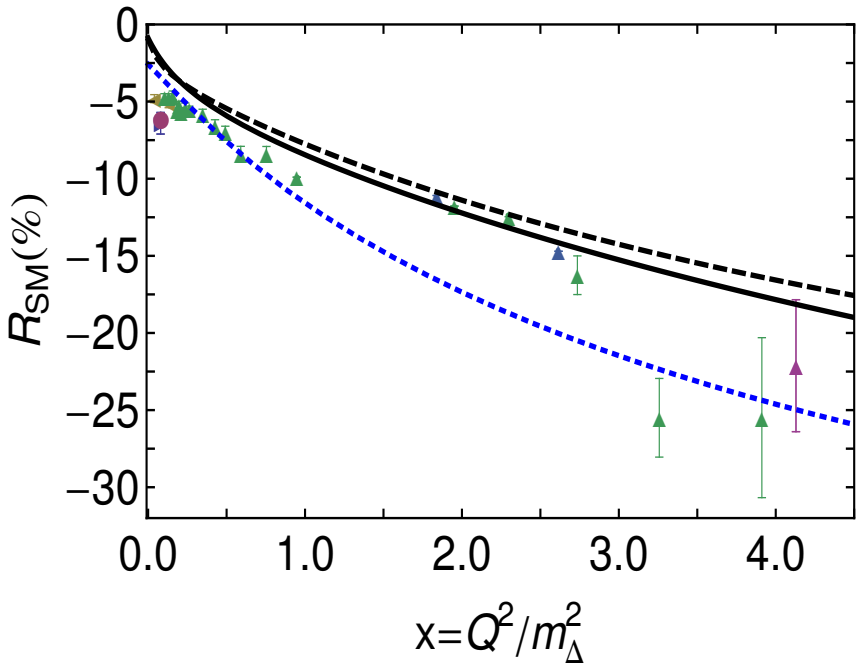
# The electric- and coulomb-quadrupole ratios

☞ $R_{EM} = R_{SM} = 0$ in SU(6)-symmetric CQM.

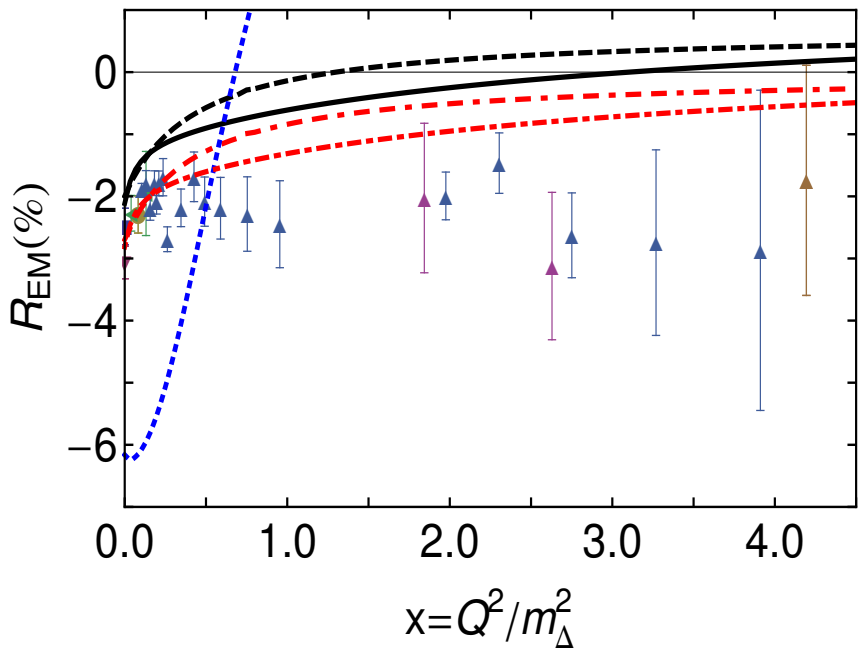
- Deformation of the hadrons involved.
- Modification of the transition current.




☞ $R_{SM}$: Good description of the rapid fall at large momentum transfer.




☞ $R_{EM}$: A particularly sensitive measure of orbital angular momentum correlations.




☞ *Zero Crossing in the electric transition form factor:*

*Contact interaction* $\rightarrow Q^2 \sim 0.75 m_\Delta^2 \sim 1.14\ GeV^2$

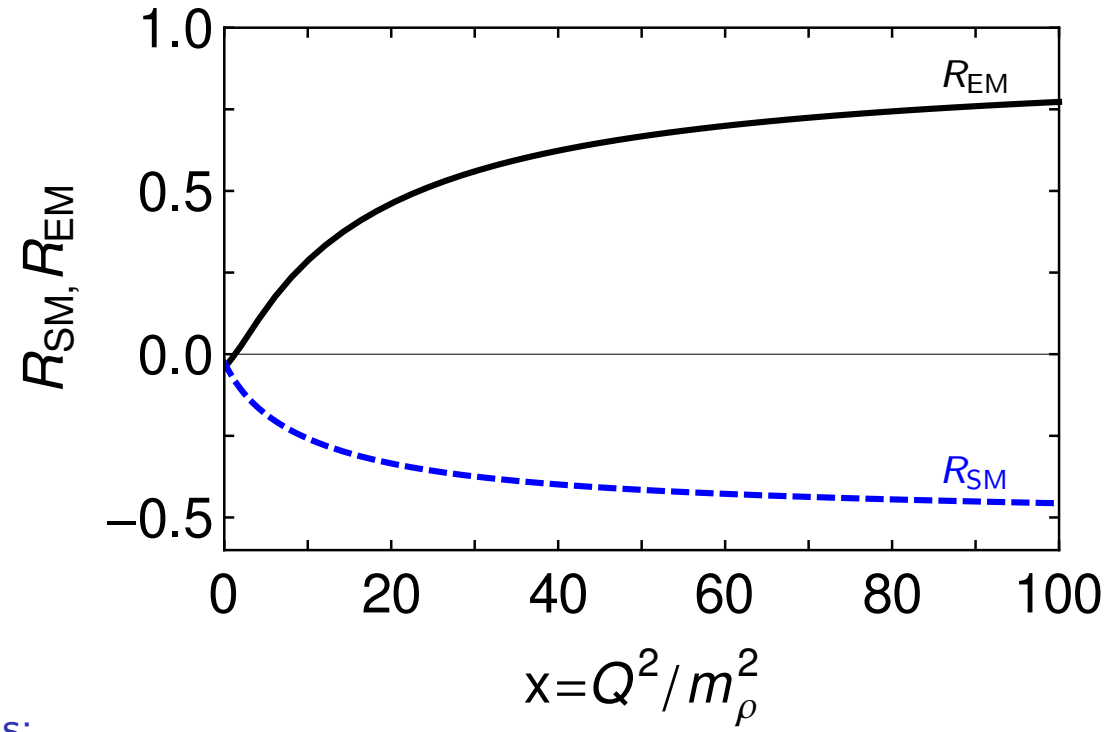
*QCD-kindred interaction* $\rightarrow Q^2 \sim 3.25 m_\Delta^2 \sim 4.93\ GeV^2$

# Large $Q^2$-behavior of the quadrupole ratios

*Helicity conservation arguments in pQCD should apply equally to:*

- *Results obtained within our QCD-kindred framework;*
- *Results produced by a symmetry-preserving treatment of a contact interaction.*

$$R_{EM} \overset{Q^2\to\infty}{=} 1\,, \quad R_{SM} \overset{Q^2\to\infty}{=} \textit{constant}\,.$$




☞ Observations:

- Truly asymptotic $Q^2$ is required before predictions are realized.
- $R_{EM} = 0$ at an empirical accessible momentum and then $R_{EM} \to 1$.
- $R_{SM} \to$ constant. Curve contains the logarithmic corrections expected in QCD.

# $\gamma^* N(940)\frac{1}{2}^+ \longrightarrow \Delta(1600)\frac{3}{2}^+$

Based on:

- **Transition form factors:** $\gamma + p \to \Delta(1232), \Delta(1600)$
  Y. Lu, C. Chen, Z.-F. Cui, C.D. Roberts, S.M. Schmidt, J. Segovia, H.-S. Zong
  Phys. Rev. D100 (2019) 034001, arXiv:nucl-th/1904.03205
- **Masses of ground-state mesons and baryons, including those with heavy quarks**
  P.-L. Yin, C. Chen, G. Krein, C.D. Roberts, J. Segovia and S.-S. Xu
  Phys. Rev. D100 (2019) 054009, arXiv:nucl-th/1901.04305
- **Spec. and struc. of octet and decuplet and their positive-parity excitations**
  C. Chen, G. Krein, C.D. Roberts, S.M. Schmidt and J. Segovia
  Phys. Rev. D100 (2019) 054009, arXiv:nucl-th/1901.04305
- **Parity partners in the baryon resonance spectrum**
  Y. Lu, C. Chen, C.D. Roberts, J. Segovia, S.-S. Xu and H.-S. Zong
  Phys. Rev. C96 (2017) 015208, arXiv:nucl-th/1705.03988

# Wave function decomposition: $N(1440)$ cf. $\Delta(1600)$

| | $N(940)$ | $N(1440)$ | $\Delta(1232)$ | $\Delta(1600)$ |
|---|---|---|---|---|
| scalar | 62% | 62% | – | – |
| pseudovector | 29% | 29% | 100% | 100% |
| mixed | 9% | 9% | – | – |
| $S$-wave | 0.76 | 0.85 | 0.61 | 0.30 |
| $P$-wave | 0.23 | 0.14 | 0.22 | 0.15 |
| $D$-wave | 0.01 | 0.01 | 0.17 | 0.52 |
| $F$-wave | – | – | $\sim 0$ | 0.02 |

## $N(1440)$

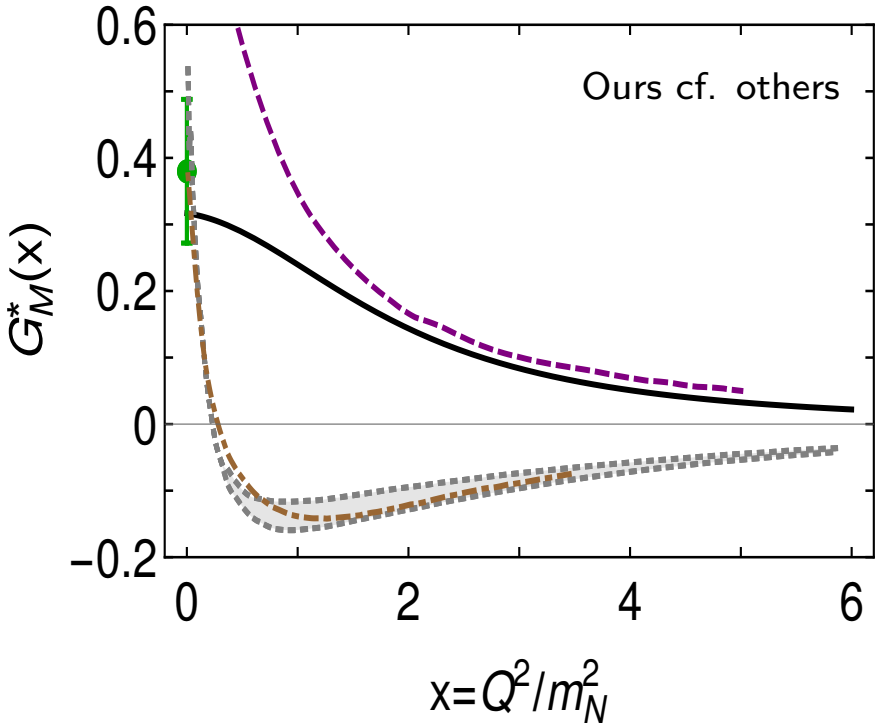
- Roper's diquark content are almost identical to the nucleon's one.
- It has an orbital angular momentum composition which is very similar to the one observed in the nucleon.

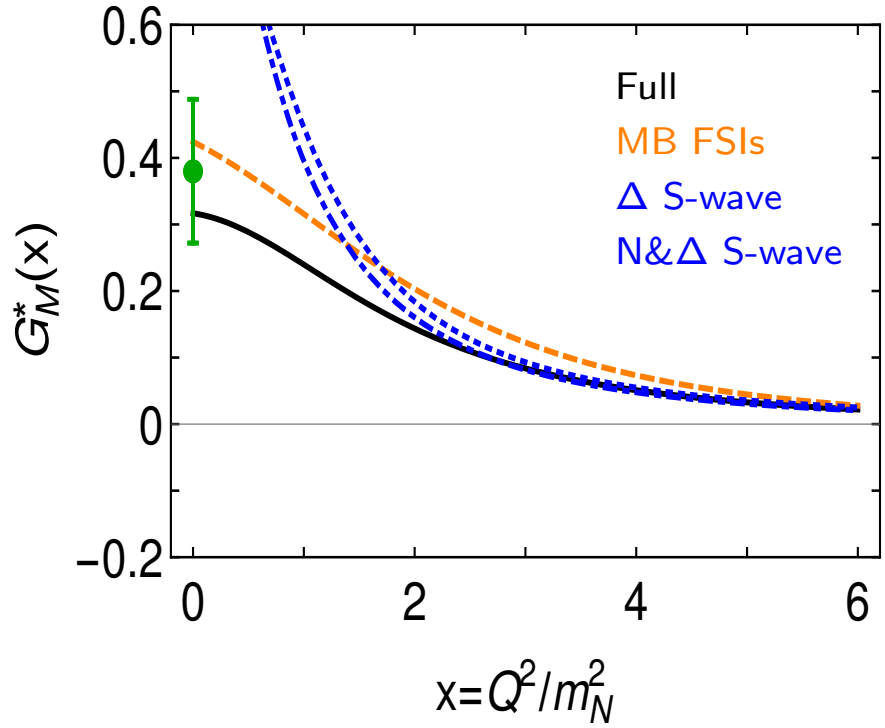
## $\Delta(1600)$

- $\Delta(1600)$'s diquark content are almost identical to the $\Delta(1232)$'s one.
- It shows a dominant $\ell = 2$ angular momentum component with its S-wave term being a factor 2 smaller.

**The presence of all angular momentum components compatible with the baryon's total spin and parity is an inescapable consequence of solving a realistic Poincaré-covariant Faddeev equation**

# The magnetic dipole form factor in the Jones-Scadron convention

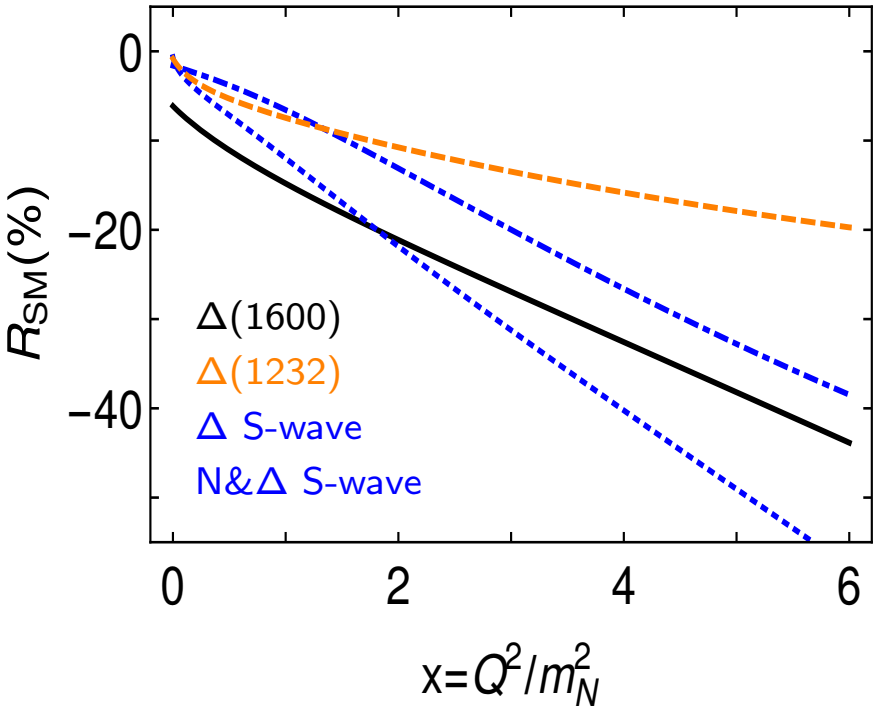


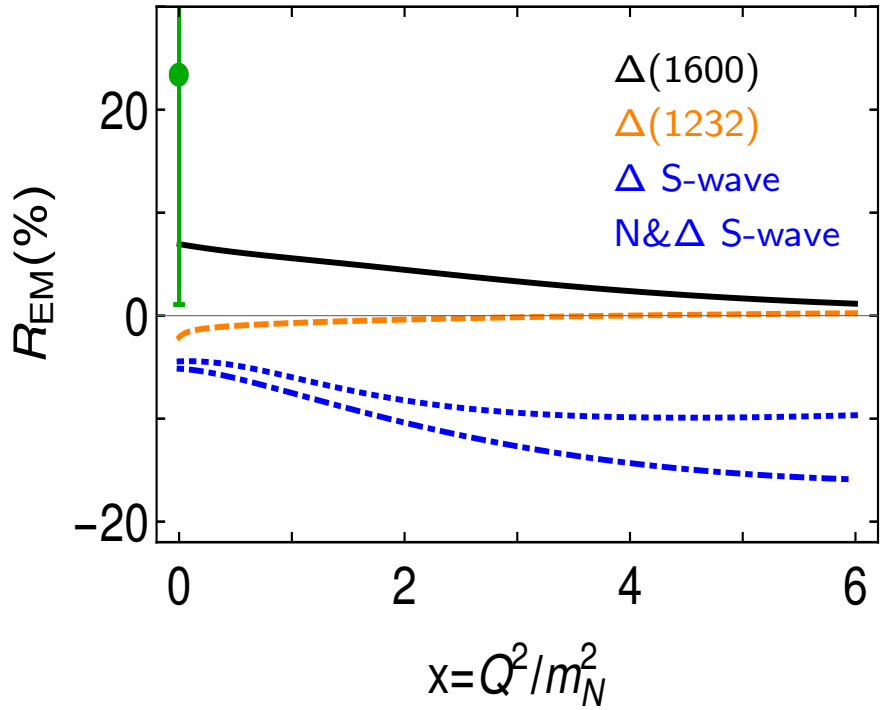




☞ Observations:

- It is positive defined in the whole range of photon momentum and decreases smoothly with larger $Q^2$-values.
- The mismatch with the empirical result are comparable with that in the $\Delta(1232)$ case, suggesting that MB FSIs are of similar importance in both channels.
- Higher partial-waves have a visible impact on $G_M^*$: They bring the magnetic dipole moment to lower values which could be compatible with experiment.

# The electric- and coulomb-quadrupole ratios




☞ Observations:

- $R_{SM}^{\Delta'} \gtrsim R_{SM}^{\Delta}$ indicating that higher orbital angular momentum components in the Δ(1600) are more important than in the Δ(1232).
- $R_{EM}$ for the Δ(1600) transition is far larger in magnitude than the analogous result for the Δ(1232) (and opposite in sign).
- Points above are an observable manifestation of important higher orbital angular momentum components in both states.
- In particular, there is an enhanced $D$-wave strength in the Δ(1600) relative to that in the Δ(1232).

# Summary and conclusions (I)

*We insist on our purpose of getting an unified study of EM elastic and transition form factors of nucleon resonances using QCD-kindred kernels and interaction vertices*

☞ **The $\gamma^*\mathrm{N} \to \mathrm{Nucleon}\,[\equiv \mathrm{N}(940)]$ reaction:**

- Proton's and neutron's electromagnetic ratios are sensible observables to disentangle fundamental quantities of QCD.
- The presence of strong diquark correlations within the nucleon is sufficient to understand empirical extractions of the flavor-separated form factors.
- Scalar diquark dominance and the presence of higher orbital angular momentum components are responsible of the $Q^2$-behaviour of $G_E^p/G_M^p$ and $F_2^p/F_1^p$.

☞ **The $\gamma^*\mathrm{N} \to \mathrm{Nucleon}'\,[\equiv \mathrm{N}(1440)]$ reaction:**

- The Roper is the proton's first radial excitation. It consists on a dressed-quark core augmented by a meson cloud that reduces its mass by approximately 20%.
- Our calculation agrees quantitatively in magnitude and qualitatively in trend with the data on $x \gtrsim 2$. The mismatch on $x \lesssim 2$ is due to meson-cloud contribution.
- CLAS12@JLab will test our predictions for the charged and neutral channels in a range of momentum transfer larger than $4.5\,\mathrm{GeV}^2$.

# Summary and conclusions (II)

☞ **The $\gamma^* \mathrm{N} \to \mathrm{Delta}\,[\equiv \Delta(1232)]$ reaction:**

- $G^{*p}_{M,J-S}$ falls asymptotically at the same rate as $G^p_M$. This is compatible with isospin symmetry and pQCD predictions.
- Data do not fall unexpectedly rapid once the kinematic relation between Jones-Scadron and Ash conventions is properly account for.
- Limits of pQCD, $R_{EM} \to 1$ and $R_{SM} \to$ constant, are apparent in our calculation but truly asymptotic $Q^2$ is required before the predictions are realized.

☞ **The $\gamma^* \mathrm{N} \to \mathrm{Delta}'\,[\equiv \Delta(1600)]$ reaction:**

- $G^*_M$ and $R_{EM}$ are consistent with the empirical values at the real photon point, but we expect inclusion of MB FSIs to improve the agreement on $Q^2 \sim 0$
- $R_{EM}$ is markedly different for $\Delta(1600)$ than for $\Delta(1232)$, highlighting the sensitivity of $G^*_E$ to the degree of deformation of the $\Delta$-baryons.
- $R_{SM}$ is qualitatively similar for both $\gamma^* N \to \Delta(1600)$ and $\gamma^* N \to \Delta(1232)$ transitions, still larger (in absolute value) for the $\Delta(1600)$ case.